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TRANSVERSE ENERGY DISTRIBUTION MEASUREMENTS FOR POLYCRYSTALLINE AND (100) COPPER PHOTOCATHODES WITH KNOWN LEVELS OF SURFACE ROUGHNESS

L.B. Jones[1,3*], D.P. Juarez-Lopez[2,3], B.L. Militsyn[1,3], C.P. Welsch[2,3] & T.C.Q. Noakes[1,3]

[1] ASTeC[†], STFC Daresbury Laboratory, Warrington, WA4 4AD, United Kingdom
[2] Department of Physics, University of Liverpool, L69 7ZE, United Kingdom
[3] The Cockcroft Institute, Warrington, WA4 4AD, United Kingdom

Abstract

The minimum achievable emittance in an electron accelerator depends strongly on the intrinsic emittance of the photocathode electron source. This is measurable as the mean longitudinal and transverse energy spreads in the photoemitted electrons.

ASTeC constructed the Transverse Energy Spread Spectrometer (TESS) experimental facility to measure both the transverse and longitudinal electron energy spectra from III–V semiconductor, multi–alkali and metal photocathodes. Our R&D facilities also include in–vacuum quantum efficiency measurement, XPS, STM, plus ex–vacuum optical and STM microscopy for surface metrology.

Photocathode intrinsic emittance is strongly affected by surface roughness, and the development of techniques to manufacture the smoothest photocathode is a priority for the electron source community. We present energy distribution measurements for electrons emitted from polycrystalline and single–crystal (100) copper photocathodes as a function of their measured surface roughness.

INTRODUCTION

The intrinsic emittance of a photocathode is the combination of many physical attributes such as composition, crystal face, surface roughness, cleanliness, work function and quantum efficiency (QE). Intrinsic emittance defines the lowest achievable limit of emittance in a well–configured linear accelerator, and in the absence of space charge, the source emittance can be preserved throughout acceleration in machines of this class [1]. The impact of reducing intrinsic emittance is therefore significant, and can potentially reduce both the physical size and capital cost of a Free-Electron Laser (FEL) facility driven by such an accelerator [2] while also increasing the X–ray beam brightness and hence the machine performance.

The issue of surface roughness is of particular interest to the photocathode community. It affects both the local electric field on a microscopic scale and hence the surface voltage which impacts on the accelerating field experienced by photoelectrons [3,4], and also the Schottky voltage which changes the effective work function [5] and subsequently the quantum efficiency. Surface roughness also affects the emission geometry which couples directly into mean transverse energy thereby driving emittance growth [6]. Modelling the overall effect of these physical attributes is complex, but work continues to simulate the effects of photocathode surface roughness on transverse energy and compare this with experimental data [7].

ASTeC's[†] Transverse Energy Spread Spectrometer (TESS) experimental facility is directly connected to a Photocathode Preparation Facility (PPF) [8] and can be used with III–V semiconductor, multi–alkali and metal photocathodes to measure transverse and longitudinal energy distribution curves (TEDC and LEDC respectively) [9, 10]. The factors which affect photocathode performance require a suite of diagnostic techniques, and our R&D facilities also include XPS, LEED and AFM/STM on our SAPI (Surface Analysis, Preparation and Installation) system [11], with ex–situ interferometric optical and AFM microscopes for surface roughness measurements. We have a range of laser and broadband light sources which permit QE measurements at various wavelengths on different cathode materials.

Recently, the TESS experimental system has been upgraded to increase detector performance, and the TESS now includes a significantly improved external light source. We have re–commissioned TESS and carried–out TEDC measurements at a range of illumination wavelengths for copper photocathodes with known levels of surface roughness.

TESS UPGRADE AND COMMISSIONING

The TESS detector was originally designed as a general–purpose instrument to image the photoemission footprint of semiconductor photocathodes under illumination by solid–state laser modules [9]. The detector combined 3 independent grid meshes with a microchannel plate (MCP) electron multiplier and a P43 ITO phosphor screen, using a sensitive camera to record the electron emission footprint.

The upgraded detector uses a single demountable grid mesh which still permits the same transverse and longitudinal energy spread measurements to be performed, but with increased sensitivity as the effective instrument transmission to the MCP rises from 51 % to 80 %. The photocathode illumination light source has also been replaced with a broadband Energetiq EQ–99 laser plasma–driven light source coupled using nitrogen–purged off–axis parabola op-

* lee.jones@stfc.ac.uk
† ASTeC: Accelerator Science and Technology Centre

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tics to a Bentham TMC300 $f/4$ monochromator with two diffraction gratings, one optimised for UV (250 nm blaze) and the other for visible light (500 nm blaze). The upgraded light source delivers considerably higher flux over the range $\lambda = (200 - 800)$ nm, but particularly at UV wavelengths, and includes a beam–profile camera sensitive over this entire range to ensure optimal beam properties. These improvements have allowed us to reduce the spectral width of the light spot delivered to the photocathode compared to our previous light source [12] while still achieving sufficient intensity to measure the transverse energy distribution curve.

Detector Commissioning

Commissioning measurements were carried out using a GaAs photocathode activated to a QE of around 4 % at a wavelength of 532 nm. Measurements were made under illumination at wavelengths $\lambda = (500, 550, 600, 650)$ nm with the light spot focussed to around 120 µm FWHM at the cathode surface. The cathode was biased at −25 V, with the grid and MCP front plate biased at 25 V. The drift distance between the photocathode surface and the grid was 25.8 mm, with 4.2 mm between the grid and MCP front. MCP back was operated at 750 V and the fluorescent screen at 4 kV.

Data and dark images were recorded for all wavelengths measured, each with a typical exposure time of 30 s. This allowed pixel–by–pixel background subtraction to generate a true photoemission footprint. With knowledge of the overall accelerating voltage (and therefore the electron flight time) between the vanishingly small emission point on the photocathode surface and the MCP surface, this electron emission footprint was converted into a normalised transverse energy distribution curve or TEDC [9].

Table 1 summarises the values for mean transverse energy (MTE) extracted from the TEDC. Figure 1 shows the progressive fall in MTE as the illumination wavelength is increased and the photon energy decreases and approaches the band gap energy ($E_g = 1.42$ eV). An experimental error of ±7.5 % was ascribed to these data points. The slope and intercept of the exponential fit to the data indicates that the cathode is in a state of positive electron affinity.

Table 1: Summary of extracted MTE values for a GaAs photocathode under illumination at various wavelengths

Illumination Wavelength, λ [nm]	MTE, [meV]
500	111
550	74
600	49
650	30

EXPERIMENTAL DETAILS

Continuing from work already published investigating the link between MTE and surface roughness [13], we used the upgraded TESS detector and lightsource to measure the TEDC and MTE for a set of copper photocathodes.

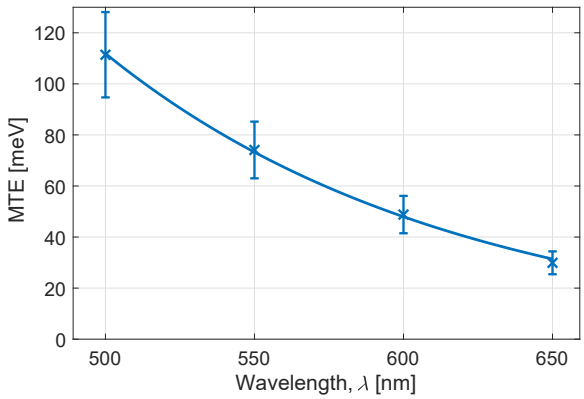

Figure 1: MTE as a function of illumination wavelength for a GaAs photocathode with quantum efficiency around 4 %.

Samples and Preparation

Experiments were performed on three 6 mm diameter copper photocathode samples whose purity was to the 6N level, purchased from Surface Preparation Laboratory. The sample designations, surface specification and roughness (R_a) are:

- **Cu.Poly** – polycrystalline surface, $R_a = 0.03$ µm
- **Cu.100P** – single–crystal (100) face, $R_a = 0.03$ µm
- **Cu.100R** – single–crystal (100) face, $R_a = 3.0$ µm

All photocathode samples were degreased in an acetone bath for 10 minutes, then Ar plasma treated in an ex–situ Henniker Plasma HPT–200 for 20 minutes at 200 W. They were then transferred into the PPF loading chamber and placed under vacuum. Each cathode received a heat clean at 450 °C for 1 hour in the PPF cleaning chamber before being transferred to the PPF preparation chamber for storage. Prior to transfer into the TESS system, the cathodes were heat cleaned again at 450 °C for 1 hour – previous work using XPS in our SAPI system has shown that this leaves the photocathode surface atomically clean [11].

Energy Spread Measurement

TEDC measurements were made and data analysed following the procedure outlined earlier and already published [9, 10]. The source bias was −60 V, with the grid and MCP front held at 40 V. The source–detector drift distance was un–changed from that described in the earlier detector commissioning measurements. MCP back was typically operated at 1230 V and the fluorescent screen at 4 kV.

EXPERIMENTAL RESULTS

Figure 2 shows the family of exponential curves fitted to the TEDC data taken for the polished polycrystalline sample (Cu.Poly). Curves for the other samples are not shown as they are very similar. The MTEs for all photocathode samples extracted from their exponential fits are presented in Table 2. Figure 3 summarises the MTEs as a function of illumination

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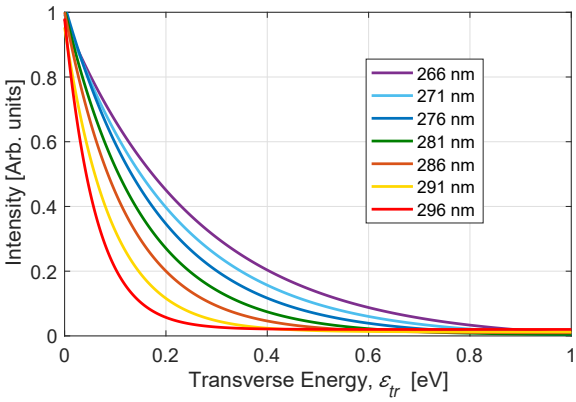

Figure 2: Summary of TEDC fitted curves as a function of illumination wavelength for the Cu.Poly photocathode.

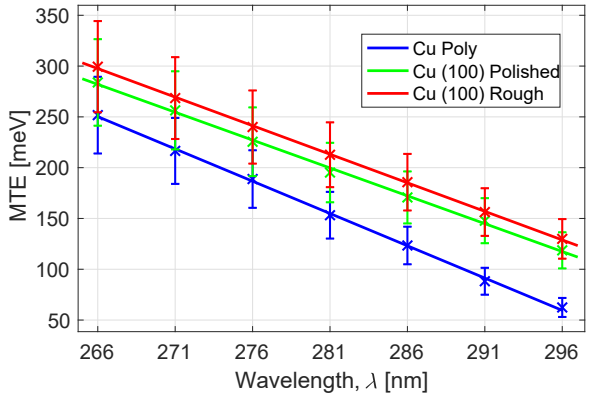

Figure 3: Summary of MTEs as a function of illumination wavelength (λ) for all photocathode samples.

wavelength, λ. An experimental error of ±7.5 % was applied to all data points.

DISCUSSION

The MTEs we present for these new copper photocathodes are systematically higher than those we have measured previously for similar samples [13]. There are several possible reasons for this.

Our assumption that we have clean photocathode surfaces may be incorrect. The previous samples to which our cleaning procedure had been applied successfully were subjected to XPS analysis, so we were able to confirm that they were atomically clean. The new samples used in this paper have not been tested with XPS due to time constraints.

The flux from our laser–driven plasma light source is more than 10 times higher than that of our previous light source at UV wavelengths. The optical bench used has also achieved a higher level of focussing, thereby reducing the spot size at the photocathode surface compared to our previous setup. These two factors combine to deliver a significantly higher flux density at the photocathode surface, potentially creating space charge effects in the measured data. This will drive an increase in measured TEDC and the extracted MTE.

Figure 3 shows that the MTEs measured for the (100) rough surface are systematically higher than those for the (100) polished surface. Both samples are from the same material batch, so have the same chemical composition. This increase in MTE fits with expectations for the direct effects of surface roughness on photocathode performance.

Figure 3 also shows that the polycrystalline sample exhibits the lowest MTE of the samples measured. Data provided by the manufacturer states an average grain size of the order of 600 – 700 µm, which is considerably smaller than the illumination spot size. The workfunction for a Cu (111) surface is 0.3 – 0.4 eV higher than that of the (100) surface [14, 15], so if we are illuminating a high–workfunction facet of the sample then we should expect to see a reduction in MTE.

Table 2: Summary of extracted MTE values for copper photocathodes under illumination at various wavelengths, λ

Wavelength λ [nm]	Sample, MTE [meV]		
	Cu.Poly	Cu.100P	Cu.100R
266	252	284	299
271	216	257	268
276	189	225	240
281	153	195	213
286	124	171	186
291	88	149	156
296	62	119	130

CONCLUSIONS

Our measurements on Cu (100) samples with surface roughness R_a = 0.03 µm and R_a = 3.0 µm respectively confirm that the MTE increases with surface roughness.

FURTHER WORK

Our first priority is to establish why the MTE values presented in this paper are systematically higher than those we measured previously – is this due to our experimental parameters or the new samples.

Further measurements will be taken using the copper samples described above with their surfaces progressively–roughened. The same measurements will also with a (111) single–crystal copper surface for comparison and to explore the effects of surface roughness on MTE more thoroughly.

We plan additional work on other photocathode materials such as nickel, silver, molybdenum, niobium, lead and magnesium.

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